Investigating the Relationship Between Fin and Blue Whale Locations, Zooplankton Concentrations and Hydrothermal Venting on the Juan de Fuca Ridge

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LONG-TERM GOALS

We are investigating the potential correlation between whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge with the long-term goal of understanding such correlations in terms of the influences of globally distributed hydrothermal plumes on the trophic ecology of the deep ocean.

OBJECTIVES

We are conducting a retrospective study using existing seismic and bio-acoustical data sets from the Juan de Fuca Ridge with the following four objectives:

1. Implementing an automatic algorithm to track fin and blue whales using data from a small-scale seafloor seismic network.

2. Tracking vocalizing fin and blue whales above the Endeavour segment over a 3-year interval from 2003-2006 in order to determine whether they are preferentially found above the hydrothermal vent fields where the bio-acoustical data show that the zooplankton concentrations are higher at all depths.

3. Analyzing a total of 60 net tow samples from the Endeavour Segment from 1995 and 1996 and combining these with 119 previously analyzed net-tow samples from 1991-1994 to refine our understanding of the variations of zooplankton concentrations at different depths with distance from the vent fields.

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4. Using the simultaneous acoustic backscatter and net tow data to calibrate the acoustic observations so that we can make use extensive acoustic Doppler current profiler (ADCP) data sets that already exist for the region (as well as ADCP data that may be collected in the future) to estimate zooplankton concentrations.

APPROACH

The central portion of the Endeavour Segment of the Juan de Fuca Ridge (129°W, 48°N) hosts several large hydrothermal vent fields (Figure 1) and has been extensively studied by marine geoscientists for over two decades. It is presently one of three sites at which NSF's RIDGE2000 program is conducting Integrated Studies. In summer 2009 the NEPTUNE Canada program, based at the University of Victoria, is scheduled to deploy instruments on a regional cabled observatory off the coast of Vancouver Island that will include a node at the Endeavour site.

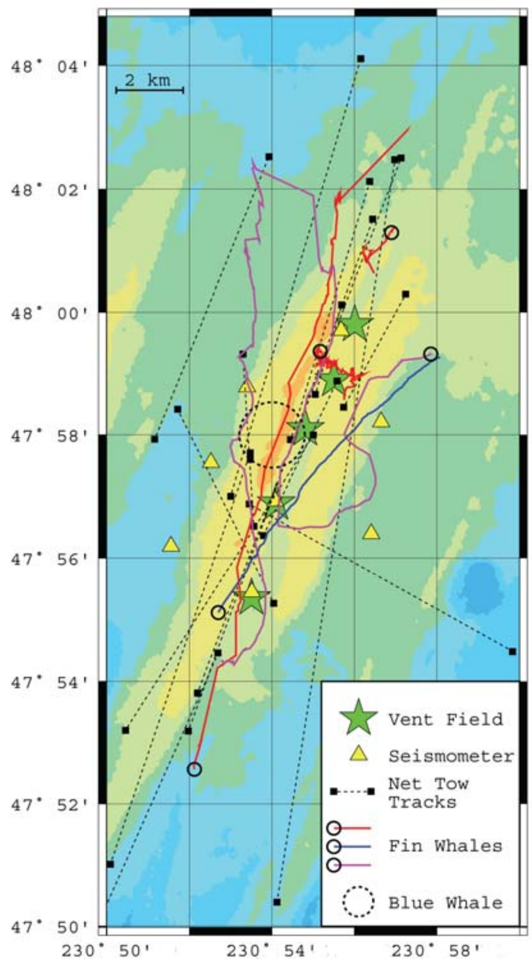

Figure 1. Bathymetric map (color changes every 100 m, blue colors at depths greater than 2500 m) showing the location of the Endeavour hydrothermal vent fields (green stars), seismometers deployed from 2003-2006 (yellow triangles), ship tracks for net tows obtained from 1991-1995 (black squares and dashed lines), preliminary tracks for four fin whales (colored lines with a black circle at the start of the track), and the location of a blue whale that stayed within a small region within the network for over 24 hours (dashed circle).

From 2003-2006, the W. M. Keck Foundation has supported a prototype NEPTUNE experiment at Endeavour and some ongoing instrument development to investigate the linkages between geological deformation, fluid fluxes across the seafloor, and microbial productivity. As part of this effort, a remotely operated vehicle was used to deploy 8 sub-bottom three-component seismometers. The network (Figure 1) spanned a region measuring ~10 km along the ridge axis and ~6 km across and operated for over three years from Summer 2003 to Fall 2006. During the earthquake analysis we have noted that the seismic records include a very extensive data set of high-quality fin and blue whale vocalizations. From the late fall to early spring there are almost daily sequences of fin whale vocalizations and without a systematic search over half a dozen sequences of blue whale calls were also noted in 2003-4. Example of fin and blue whale calls are shown in Figures 2 and 3.

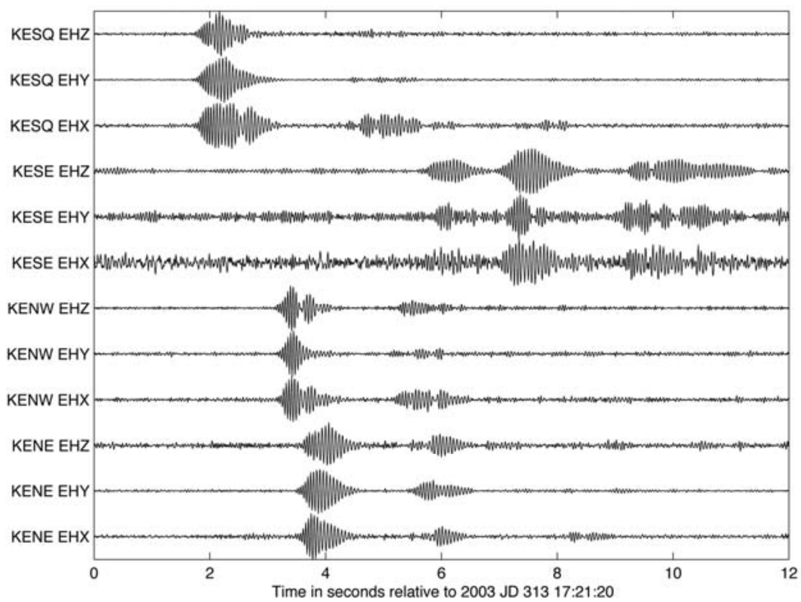

Figure 2. Examples of a fin whale vocalization recorded on four three-component seismometers (the labels EHZ, EHY and EHX indicated the vertical (Z) and horizontal channels (X and Z) of stations KESQ, KESE, KENW and KENE). The records have been adjusted to equal maximum amplitude. The fin whale was located near the network. Note that the 1st and 2nd water column multiples are clearly visible following the direct arrival.

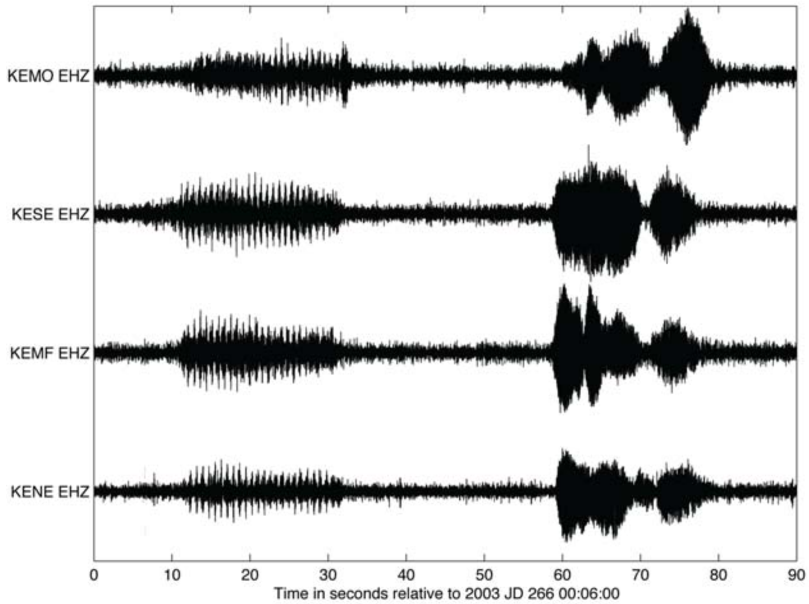

Figure 3. Examples of a blue whale vocalization recorded on the vertical channel of four stations. The "A" and "B" calls are included within the window.

Our initial approach to tracking whales has been to pick manually the first observable arrival on each ocean bottom seismometer (OBS) and then to located the whale assuming that it is at the sea surface and that the arrival is for a direct water path. This is a time consuming approach but demonstrates that we can track whales well when they are within or close to the network.

However, once the distance to the seafloor OBS exceeds ~10-12 km the amplitude of the direct arrival decreases markedly. Arrival time picks at significantly larger ranges are almost certainly for an indirect 'bounce' path (often termed a water column multiple) that includes reflections from the seafloor and the sea surface. Since our network has an aperture of 10 km, locations that are based on the assumption of direct paths will be compromised when the whale is more than a few kilometers outside the network. We could improve the locations by excluding picks from more distant stations but a better approach is to model these secondary arrivals since their timing places strong constraints on the range (McDonald & Fox, 1999). Previous work on the Juan de Fuca Ridge has demonstrated that the fin whales can be tracked to distances of ~20 km from a seafloor network by incorporating the 1^{st}, 2^{nd} and 3^{rd} reflected paths in the analysis (McDonald *et al.*, 1995).

Our approach to automatically tracking whales is to adapt a MATLAB algorithm that we have developed to automatically locate earthquakes (Weekly *et al.*, 2007). This will be a three-step process. First, we will use the ratio of short-term and long-term running RMS averages on the vertical channels of the OBSs, to identify triggers and identify them as possible whale calls if their spectra are dominated by energy near 20 Hz. Second, we will find potentially locatable whale calls by finding groups of nearly coincident whale triggers on multiple OBSs. Third, we will pick the whale call arrivals and locate them by modeling the direct and water path multiple arrivals. To pick the whale arrivals, we will calculate an envelope function and will explore options of picking each arrival at its onset, its maximum amplitude, or at the time where half the energy of the arrival comes before and after the pick. To locate the fin whales we will initially determine an approximate range and bearing

based on which OBS has the earliest arrival, the amplitudes and spacing of arrivals on each OBS, and the location of earlier whale calls in the sequence. We will then apply a grid search method using travel times calculated with the ocean acoustical ray-tracing software RAY (Bowlin *et al.*, 1992) that take into account the bathymetry to find the location that minimizes the misfit to the picked arrival times. For blue whales additional complications arise because their vocalizations are sufficiently long that the arrivals all overlap making picks of secondary reflected arrivals difficult (McDonald & Fox, 1999). While it may be possible to use the three component data to detect changes in the incidence angle associated with secondary arrivals, it may prove necessary to use relative amplitudes to constrain ranges (McDonald *et al.*, 1995).

In the early to mid-1990s, Richard Thomson and Brenda Burd at the Institute of Ocean Sciences in Sidney, BC conducted annual summer cruises to the Endeavour to collect surface to bottom temperature, salinity, light attenuation and acoustic backscatter intensity measurements that were coupled with a series of plankton net tows. The towed instrument package was designed such that biomass could be sampled at six distinct depths or depth ranges. The locations of net tows are shown in Figures 1 and 4. A total of 119 mixed faunal zooplankton net samples collected between 1991-1994 have been previously analyzed and show an enhanced zooplankton concentrations at all depths above the hydrothermal vent fields in comparison to stations 10 to 50 km off-axis (Burd & Thomson, 1994, 1995). At depth, the zooplankton were concentrated in a 100-m-thick layer of increased acoustic backscatter near the top of the hydrothermal plume at 1.9 km depth (Thomson *et al.*, 1991, Burd *et al.*, 1992), leading to the inference that the zooplankton were taking advantage of the chemosynthetic bacteria, fine grained particulates and other nutrients carried by these plumes while avoiding the highest concentrations of chemicals in the plume cores. Zooplankton biomasses in the normal near surface scattering layers (< 400 m) were elevated but highly variable, reflecting the diurnal migration of fauna in the euphotic zone and were underlain by a permanent mid-depth scattering layer (400-800 m) which also had increased zooplankton concentrations relative to sites off axis (Burd & Thomson, 1994). Community analysis revealed that the deep faunal assemblages above the vents (but not elsewhere) where infiltrated by shallow faunal species including a large number of filter feeding copepods and their predators (Burd & Thomson, 1994, Burd & Thomson, 1995). This suggests that shallow zooplankton migrate vertically between the upper ocean and the hydrothermal plume (Burd & Thomson, 1994). This interpretation is consistent with a simple circulation model which suggests that zooplankton can make the round-trip journey before being advected away from the hydrothermal plume (Burd & Thomson, 1994) and it can explain the increased biomass observed at all depths.

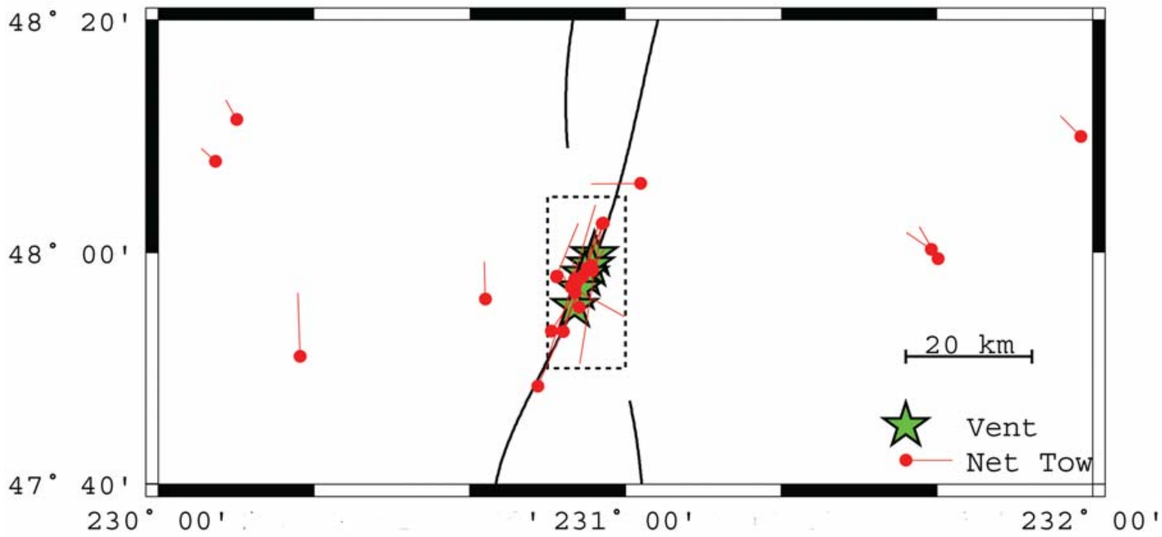

Figure 4. Regional map showing the location of the Endeavour vent fields (green stars), ship tracks for net tows in 1991-1996 (red line with a red circle at the start of the track), the location of the spreading ridge axis (solid line) and the area covered by Figure 1 (dashed line).

We plan to analyze an additional 60 net samples that were collected from the area in 1995-1996. For each net sample we know the depth, location and time, and we will identify major zooplankton and fish species and determine length, gender, stage of development, and dry/wet biomass. The expanded zooplankton data set will be used to refine our understanding of variations in zooplankton concentrations with distance from the hydrothermal vent fields. We will compare variations in near surface zooplankton concentrations with spatial variations in the incidence of vocalizing whales.

The data we have collected on zooplankton distribution and biomass in the water column overlying Endeavour Ridge have several factors which make them uniquely suited to acoustic calibration of net samples. Specifically, the ADCP was mounted just below a 330 μm mesh, 1-m^2 opening/closing multiple-net apparatus which was towed obliquely through the water column (Burd & Thomson, 1993, Burd & Thomson, 1994). This configuration produced acoustic and faunal data which were concurrent in both time and space. Secondly, the attitude sensors and three-dimensional current measuring capabilities of the ADCP allowed us to determine the flow volume through the nets with only 2 to 3% error (Burd & Thomson, 1993), and thus, obtain accurate volume-adjusted estimates of the contribution of each acoustic ensemble to the total zooplankton biomass. We are unaware of any other studies in which the acoustic device was towed simultaneously with a multiple net array for concurrent and proximate data collection. In addition, there have been no previous efforts to simultaneously calibrate net and acoustic data collected from diverse habitats or over an extended time period. This is because acoustic calibrations have tended to be least accurate when samples are compared for different diurnal periods, different cruises, and when net avoidance is an issue.

The present study of zooplankton distribution and ecology near a mid-ocean ridge hydrothermal venting region includes net samples collected over a 200 km lateral distance, from the surface down to 3000 m depth, at all times of the day and night, over a period of six years. Because of the broad spatial and temporal coverage, the mix of faunal types and sizes varied considerably among net samples. We suggest that previous attempts at acoustic calibration of net biomass using ADCPs were severely

hampered by the fact that nets were not collecting fauna at the same time and place as the volume of water being ensonified. Backscatter data collected close to the transducer are likely to be most accurate for biomass estimation because the acoustic signal is less distorted by attenuation and the signal-to-noise ratio is high. Acoustic backscatter obtained from a 153 kHz RD Instruments ADCP mounted immediately below a towed multiple net apparatus should accurately determine the biomass in highly mixed species net samples collected over a broad range of depths and oceanic conditions.

A close regressional relationship between the biomass and acoustic backscatter (for the specified scattering cross-sectional model) means that profile acoustic data can be used to map three-dimensional distributions of biomass in the vicinity of the ridge without the need for expensive and labor intensive net sampling tows.

WORK COMPLETED

The award was processed by the University of Washington Grants and Contracts Office in late spring 2008. We have made significant progress over the summer and are on track to complete the work planned for the first year.

At the University of Washington, we have expanded on our initial efforts to track a few whales manually using the direct arrivals. To date, undergraduate student Elizabeth McHugh has systematically picked and located whale vocalizations using direct arrivals for a 2-week period. This catalog will provide a control data set to test the automatic location algorithm. Our goal is to extend this manual catalog to cover 4-weeks by the end of 2008.

Incoming graduate student Dax Soule has modified the first two steps of our automatic earthquake location algorithm to trigger on whale calls and then associate triggers on multiple receivers into whale events. These two steps have been successfully tested against the data set of manual locations. Dax Soule and PI William Wilcock have started exploring algorithms to pick the whale arrivals (direct and water column multiples) automatically and will combine these with an automatic location algorithm based on a grid search. As a step towards implementing the automatic algorithm, we have modeled ray paths for direct arrivals and multiples with up to five seafloor bounces using the ocean acoustical ray-tracing software RAY (Bowlin *et al.*, 1992). We have constructed tables of predicted travel times and amplitudes (Figure 5).

At the Institute of Ocean Sciences, co-PI Richard Thomson is making arrangements with to Val Macdonald (M.Sc.) at Biologica Environmental Services Limited to analyze biological samples collected from 1 m^2 Tucker trawl nets in the vicinity of Endeavour using the Canadian Coast Guard Research Vessel CCGC *John P. Tully* in 1995 and 1996.

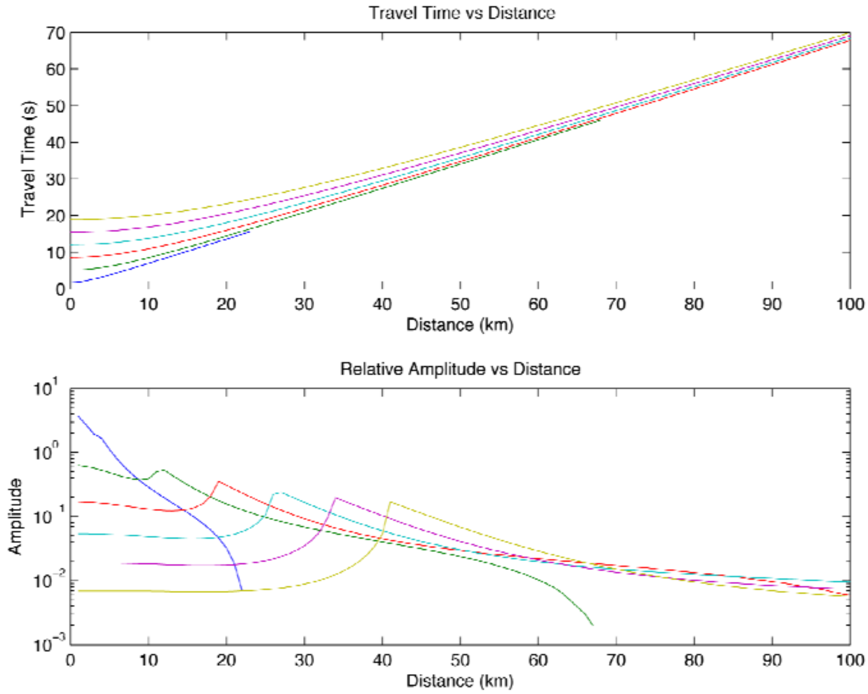

Figure 5. Predicted travel times (top) and amplitudes (bottom) for the direct (blue), 1st water column multiple (green), 2nd multipe (red), 3rd multipl (cyan), 4th multiple (purple) and 5th multiple (yellow) assuming a constant water depth of 2.5 km and a basaltic basement appropriate for the ridge axis. Amplitudes for the mulitple paths show a pronounced peak that corresponds to the critical rflection angle; this will be smoothed out when the attenuative properties of the basement are incorporated.

RESULTS

This project is still in its early a stages and we do not yet have significant results and conclusions to report.

IMPACT/APPLICATIONS

We will develop an automatic whale-tracking algorithm that can be applied to other seafloor seismic networks. If we find a close regression relationship between biomass and acoustic backscatter, we will have developed a method to reliably extrapolate limited and expensive net tow data to images of the three-dimensional distribution of biomass. If this retrospective study demonstrates a correlation between whale tracks, enhanced zooplankton concentrations and hydrothermal vents above the Juan de Fuca Ridge it will have implications for our understanding of the global influences of hydrothermal vents on the trophic ecology of the ocean. The Endeavour segment will be a node on the NEPTUNE Canada regional cabled observatory where plans call for the deployment of a seafloor seismic network and water column experiments that will monitor deep macrozooplankton concentrations, These experiments could be augmented by deploying shallow moorings equipped with ADCPs to monitor acoustic backscatter intensity in the upper water column both above the vent fields and at off-axis "background" locations. With the involvement of a zooplankton expert, these acoustic observations could be complemented and calibrated by a series of plankton tows. Year round acoustic backscatter

and whale monitoring would allow for correlations between individual whale tracks and zooplankton concentrations.

RELATED PROJECTS

The W.M Keck Foundation provided $5M to a group led by John Delaney at the University of Washington to develop prototype observatory experiments to monitor the linkages between seismic deformation, seafloor venting and microbial productivity. William Wilcock was the lead-PI for the seismic component of this project which funded the deployment and operation of the Endeavour seismic network from 2003-6.

NEPTUNE Canada is installing a regional-scale cabled observatory in the NE Pacific Ocean that will become operational in Summer 2009. The observatory includes a node at the Endeavour. Rick Thomson at the Institute for Ocean Sciences is the lead PI for a regional circulation experiment that will provide high resolution, near real-time records of current velocity, water properties (salinity and temperature), and macrozooplankton concentrations within the axial valley of the Endeavour segment of Juan de Fuca Ridge. William Wilcock is a co-PI on a seismic experiment that will occupy five of the sites developed by the Keck experiment.

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